STATUS REPORT ON AGOR*

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1) Introduction

Following the proposal by the ORSAY group [1,2,3], of a variable energy, multiparticle superconducting cyclotron accelerating protons as well as heavy ion beams, a collaboration between French and Dutch national research funding agencies has resulted in the project to study and built such an accelerator to be called AGOR (Accelerator Groningen Orsay). The project will be carried out by two laboratories : l'Institut de Physique Nucléaire d'Orsay (IPN Orsay) and the Kernfysisch Verneller Instituut of Groningen (KVI Groningen).

In December 1985 a contract was signed by the two funding agencies, establishing the operating details of this joint venture. Since that moment the construction of the AGOR machine is underway.

2) Main Design Characteristics

The machine is a compact, three sector, three dee cyclotron with an effective K=600 and a K_F = 220. The feasibility of accelerating protons up to 200 MeV implies different requirements for position and geometry of the superconducting coils, for the flutter poles and magnet structures as well as for the RF operating range as compared to other superconducting cyclotrons. Fig.1 shows the major components, the split-cryostat containing the two paires of superconducting coils, the yoke walls, the geometry of poles and valleys, the RF structures and the axial injection line.

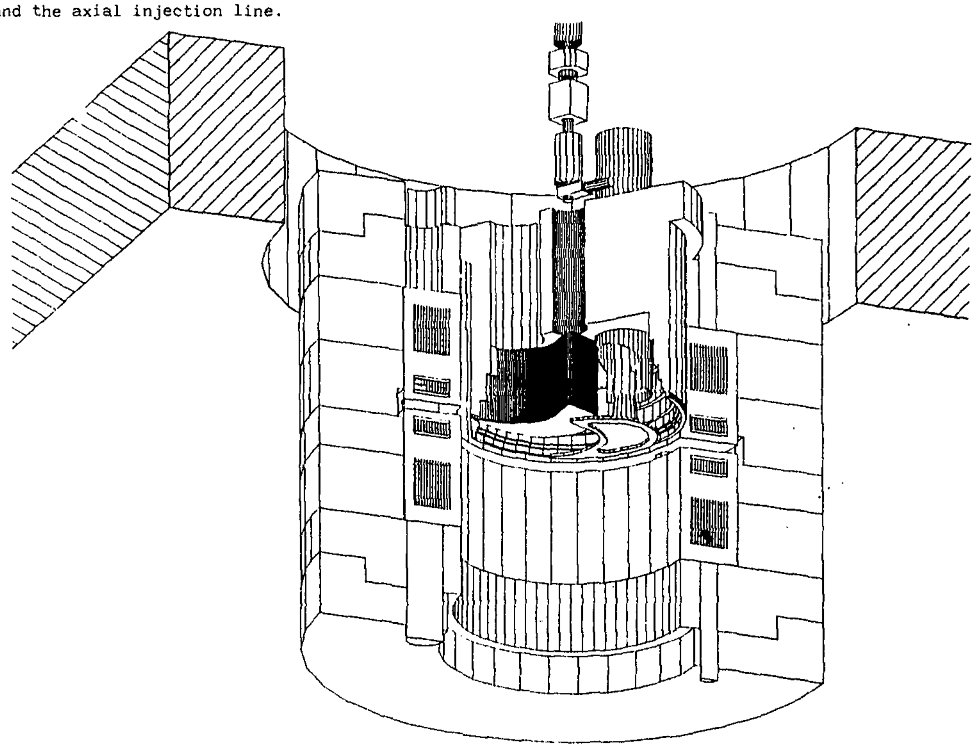

Fig.1. Simplified cutaway view of the major components.

Ion energy vs. Z/A in MeV per nucleon and boundaries of the operating range of the R.F. frequency (24 to 62 MHz) using the harmonics h = 2,3,4 are shown on fig.2.

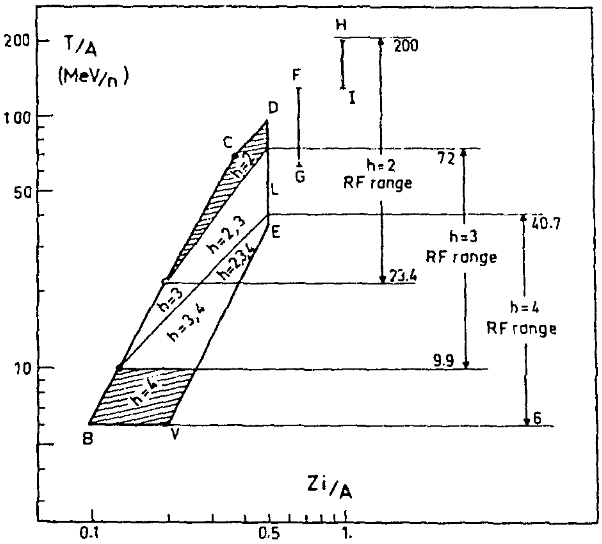

Fig.2.Ion energy vs. Z/A and boundaries of the operating RF range.

The major machine parameters are listed in table 1.

Table 1.

Bending limit	K = 600
Focusing limit	K_F = 220
Pole diameter	= 188cm
No of sectors	= 3
	No spiral for R < 30 cm
Spiral coeficient 1/20 rd/cm at R	= 70cm
1/40 rd/cm at R	= 88cm
Min hill gap	= 7cm
Min valley gap	= 84cm
Main coil 1 current density	= 4271 A/cm^2 max
Main coil 2 current density	= 3270 A/cm^2 max
Central field main-max	= 17.5 - 40.5 K Gauss
No of trim coils	= 15
Max current in trim coils	= 500 A
Number of dees	= 3 in valleys
RF range	= 24 to 62 MHz
Operating harmonics	= 2, 3, 4
Peak dee voltage at R = 0	= 85kV

The cyclotron will have T/A versus Z/A operating curves as shown in Fig.3,using external ion sources (duoplasmatron for light ions : (p,d, He) and ECR source for heavy ions with a charge to mass ratio ranging from 0.5 to 0.1).

An operating range of 24 to 62 MHz for the accelerating frequency using the three harmonics modes (h=2,3 and 4) has been chosen. The regions of the operation for the 2nd,3rd and 4th harmonics are shown in Fig.2. The majority of beams energy (10 to 72MeV /nucleon) will be accelerated on the 3rd harmonic, the more relativistics ions will use the 2nd harmonic due to limitations of the maximum RF frequency to 62 MHz and of the maximum allowable vertical components of the electric field E_z in the inflector (E_z < 25 kV/cm). For the low energy part of the diagram (10-6 MeV/nucleon) the harmonic mode h=4 will be used, the choice being to limit the minimum frequency to 24 MHz in order to minimize the mechanical displacement of the short-circuit and therefore the length of the RF resonators. The design of a central geometry compatible with the 3 harmonic modes has been considered to be a basic feature of the design and has been successfully achieved in the study [4]. The change from one harmonic mode to the others implies only a change of the inflector.

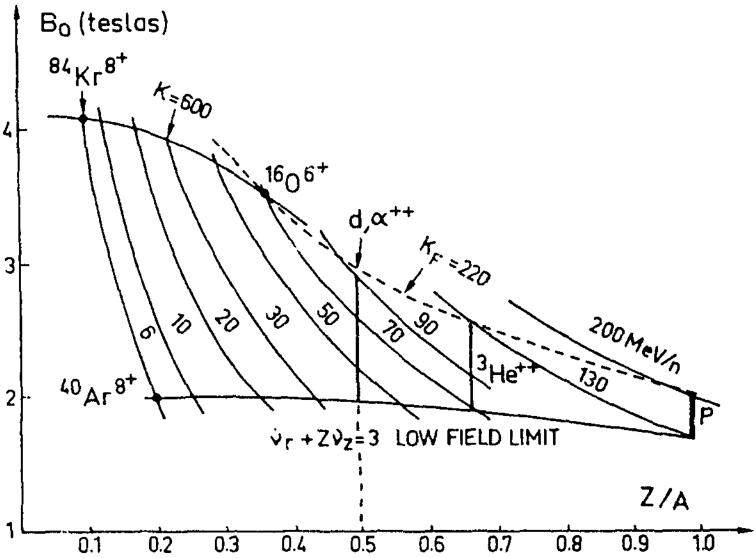

Fig.3. Operating diagram in the (Bo, Z/A) plane.

3)Magnet structure

The magnet will have a cylindrical iron yoke consisting of 8 cast steel rings, and two emovable cylindrical poles.
The main magnet parameters are given in table 2.

Table.2

Pole radius	: 94cm
Yoke inner radius	: 146cm
Yoke outer radius	: 220cm
Yoke full heigth	: 380cm
Lifting range of the upper pole	: 2.50m
Steel = cast, carbon content	< 0.04%
Total weight	: 350T

The open space between the poles and yokes which accomodates the cryostat and the superconducting coils has a radial width of 52 cm and a total axial heigth of 200cm. A novel feature of the design is the study of a split-cryostat[5] which provides excellent access to the mid plane.

Since the attractive force between the pole at full excitation is around 1400 tons, deformations of the yoke are anticipated. These effects have been calculated, neglecting in a first step the various holes, using analytical formulaes. The results show that the yoke should have an axial deformation of less than 0.2mm, by large within elastic limits. More detailed calculations are underway.

The axial hole provided for axial injection purpose has a diameter of 12.4cm in the part closest to the median plane, increasing to a diameter of 25cm to give more room for devices such as buncher, diagnostics, steering plates, solenoids, etc ...

The fifteen trim coils will be similar to those already developped at MSU and Milano[6]. Each coil has 1 layer of 5 turns of $6x5mm^2$ conductor and will carry a maximum current of 500 A. The trim coils will be covered by a vacuum enclosure, which separates them from the machine vacuum. This enclosure will at the same time be the RF liner.

4) The superconducting coils and the split-cryostat

As pointed out before the superconducting coils system consists of a pair of outer coils generating the desired overall field profile and a pair of inner coils close to the mid plane that generate a radial field gradient depending on the ion to be accelerated. The curent density needed in the two pairs of coils, J1, J2 in order to produce an isochronous field for all ions and energies have been computed. The corresponding operating diagram is shown in fig.4 where constant Bo and Z/A lines are also plotted.

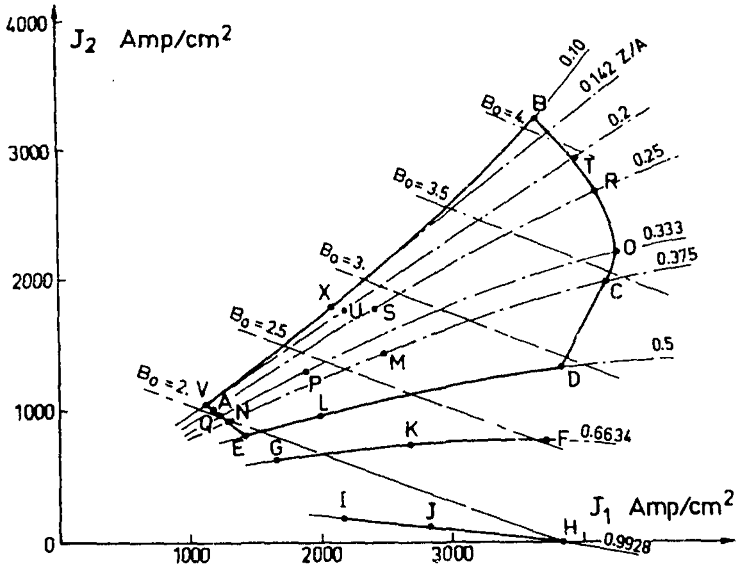

Fig.4. Cyclotron operating diagram in the(J1, J2) plane.

The diagram shows that J1 and J2 are always positive, a situation which simplifies the analyses of the forces and stresses on the coils. The geometry of the coil system is unique in the sense that a large gap exists between the inner and the outer coil of 0.325m. Due to this design the axial Lorentz forces between the coils are greatly reduced (6.6MN) in comparison with other coil systems for superconducting cyclotrons (17.0MN) allowing for only six rods support a 4.2 K between the coils in the mid-plane. As a consequence it was possible to design a split-cryostat in which room-temperature access is provided to most of the middle plane enabling an easy install (and withdrawell) of extraction elements and diagnostics probes. An overall view of the cryostat and coils is given in fig.5. The total weight of the cryostat + superconducting coil system is of about 30 tons.

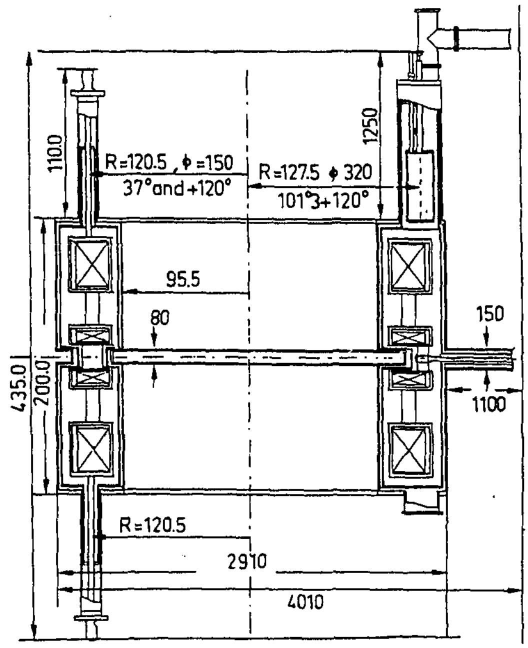

Fig.5. Overall view of the cryostat and the coils.

In table 3 are listed the main characteristics of the superconducting coils.

The superconducting coils will be fully vacuum impregnated to reduce the risk of electrical shorts between the windings and to enhance the mechanical stability.

Thermal stability of the coils is improved by liquid helium in direct contact with the winding package at all sides.

Table 3.

	Coil 1	Coil2
Inner radius	1.06m	1.06m
Outer radius	1.30m	1.30m
Width	0.08m	0.315m
Max overall current density	42.71 MA/m	32.65 MA/m
Max field strength	3.64T	4.74T
Conductor cross section (bare)	3.03x5.31mm^2	5.5x8.6mm^2
(insulated)	3.53x5.71mm^2	6.0x9.0mm^2
Cu : Sc ratio	19	26
Superconductor NbTi, rutherford cable		6
copper substrate		2
Nominal transport current	861 A	1763 A
Critical current (3.64T.6K)	1435 A	2963 A
Critical temperature	7.5K	6.5K
Conductor length (per coil)	7.1Km	11.4 Km
Conductor mass (per coil)	1200 Kg	5700 KG

5) Extraction

The extraction is accomplished by an electrostatic deflector (ESD), 38° long and two electromagnetic channels (EMC1, EMC2) positionned in two consecutive hills. A third electromagnetic channel EMC3 followed by two quadrupoles Q1, Q2 located inside the yoke are used to confine the beam along the extraction path. The main parameters of the extraction system elements are listed in table 4.

Table.4

ELEMENT	Θ_{IN}	Θ_{OUT}	(kV/cm)	Δ (KG)	δB/δx (KGauss/cm)
ESD	48°	86°	85	-	-
EMC1	168°	208°	-	3	-
EMC2	290°	330°		3	.35
EMC3	350°	20°		1.5	
Q1					1.5
Q2					- 1.5

6) Axial injection and central region geometry

The axial injection system for the superconducting cyclotron is designed to operate with 3 ion sources : a light ion source able to deliver up to a few 100μ A beams of H and He, an ECR for heavy ions and polarized light ion source. The injection line, compatible for the operation at Orsay and at KVI is shown in fig.1. It consists of unit transfer matrix cells and of 2 matching sections (one for the different ion sources, the other for the cyclotron). Because of the polarized ions, the transport line before the 90° electrostatic spherical deflector is based on electrical quadrupoles. A buncher operating at the RF of the cyclotron and common to the 3 harmonic modes h = 2, 3, 4 will be placed about 50cm from the median plane to take into account various limiting parameters (source noise, axial field,etc.)

The central region geometry has been designed in conjunction with a spiral inflector. A design study taking into account the space availability, voltage limiting, R.F. shielding as well as large gain in the first 2 electrical gaps has been carried out. The electrical equipotential surfaces have been measured on a 5 to 1 scale model allowing a detailed study of the horizontal and vertical motion.

7) R.F. System

The R.F. system consists of three compact half-wave length resonators with continuous and smooth connection to the dees.

Using the specified injection R.F. voltage vs frequencies (Fig.6) and the last mechanical drawings a new computation of the resonator has been made[7]. We have carefully adjusted the shape and position of the stem to electrode connection in order to obtain a moderate radial increase of the voltage without a too high current density in the short-circuit, minimizing at the same time the R.F. power and the length of the stem (Fig.7).

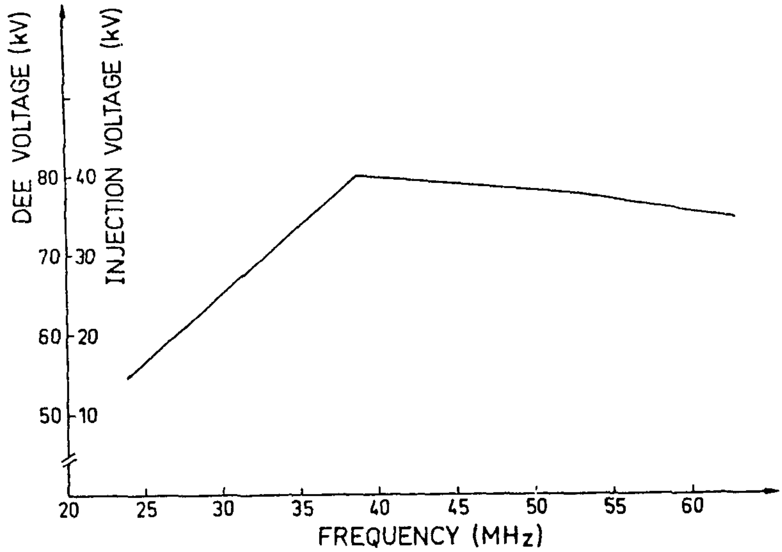

Fig.6. Injection R.F. voltage (peak) vs. frequencies.

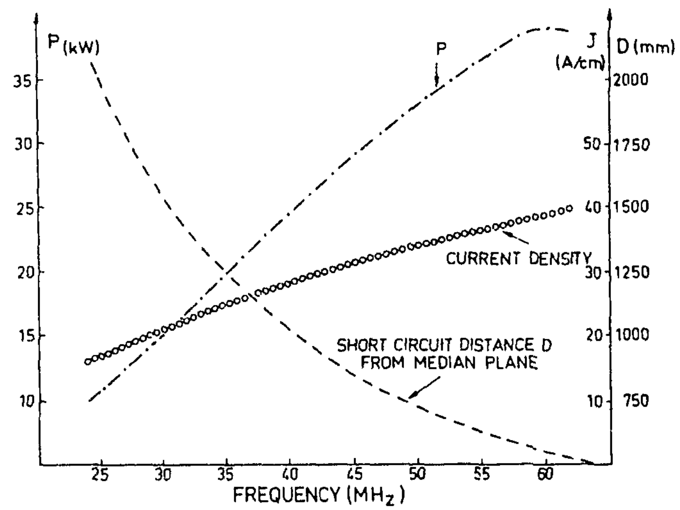

Fig.7. Power, current density, short circuit position vs. frequencies.

It is seen from the curves in fig.7 that the maximum power at 62 MHz is limited to 38 kW with a current density around 40A/cm in the short circuit. The short-circuit movement does not exceed 1.65 meter from 24 to 62 MHz.

Experiments with a specially built resonator have shown that the sliding contacts, which we have developped, withstand current densities over 80A/cm at 27 MHz, in good agreement with calculations[8].

From these measurements and from calculations it is estimated that at 62 MHz current densities up to 55A/cm can be accepted. This gives a sufficient safety factor. Experiments at 62 MHz are underway and will be finished at the end of this year.

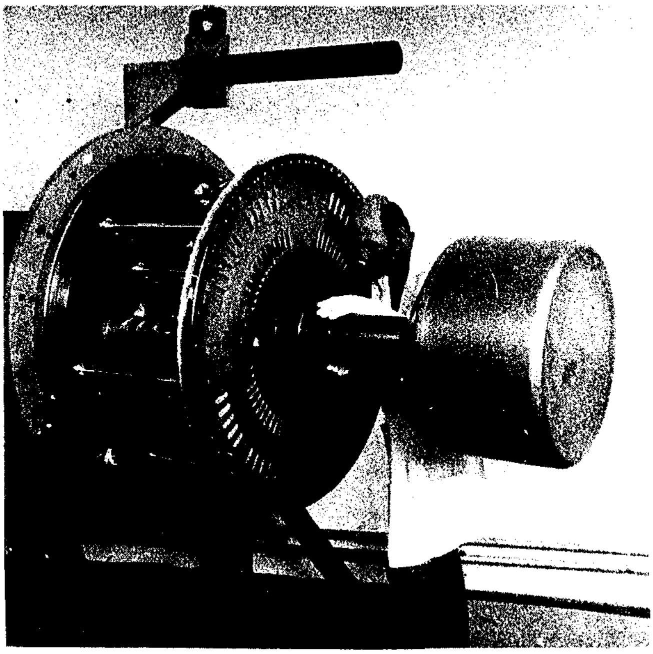

Fig.8. 27 MHz resonator for sliding contacts test.

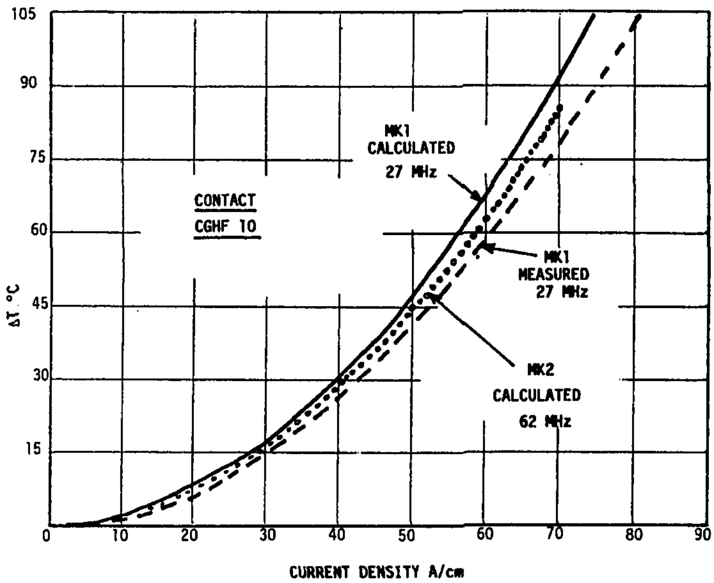

Fig.9. Experimental results and calculations for sliding contacts at 27 and 62 MHz.

The complet pre-mechanical studies are finished and a full-scale model resonator will be built to determine precisely the resonant frequencies and the voltage and current distributions and also to test the fine tuning and the coupling systems.

Furthermore the design and construction of various components of the R.F. regulation system, such as stable and accurate discriminators phase shifters, etc ... has been started.

Project status

Presently studies on the installation of the machine at Orsay are underway.

The cyclotron will be located in the building where the ALICE accelerator system was installed. The definition of an appropriate crane, the modification of the building walls and the construction of the cyclotron pit are expected to begin in the first month of 1987.

Experimental tests on the various elements of the injection line will be undertaken on a standard test bench and on a similar axial injection line of the MEDICYC cyclotron [9]. Bid for tenders for the magnetic yoke and iron of the sections will be placed at the end of this year.

A half-scale model of the R.F. cavity will be designed and constructed while detailled mechanical and thermodynamics studies will be pursued.

A prototype of the electrostatic deflector is being built.

For the cryogenic system, experiments are conducted at Delpht University on the current leads and on the radiation shield.

Elements of the control system which has a modular architecture consisting of a number of microcomputers are already being tested.

It is anticipated that the main components of the cyclotron (magnet steel, R.F. resonators and amplifiers, superconducting coils and cryostat) will be ordered during the cource of next year.

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REFERENCES

1) IPN Orsay project - First machine design studies
A. LAISNE, 9th. Int.conf. on Cyclotron and their applications, Caen (Sept.81) 203.
2) Le Projet de cyclotrons à bobines supraconductrices et l'ensemble accélérateur associé, rapport final sur les études théoriques et techniques de faisabilité, Report IPNO-GEPL Orsay (Juin 1983).
3) Minimum spiraling solutions upgrading the capacility in light ion acceleration of a supraconducting isochronous cyclotron
A. LAISNE, 10th. Conf.Int. on Cyclotron and their applications, East Lansing (Mai 1984) 288.
4) J.P. SCHAPIRA, Axial Injection System for the superconducting cyclotron AGOR. Contribution to this conference.
5) K. PIETERMAN, Design Study of the AGOR superconducting coils and criogenic system, Contribution to this conference.
6) G. BELLOMO, D.A. Johnson, P. MILLER and F.G. RESMINI Nucl. Ins. and Methods, 180 (1981) 285.
7) C. BIETH, Paramètres fondamentaux des résonateurs principaux d'AGOR, Internal Report NT/HF/30/04/86.
8) J. LEBRIS, C. GUILLAUME, Résultats des essais de contact, type AGOR 1 à 27 MHZ, NT/HF/24/01/86.

9) P. MANDRILLON et al., A 60 MeV proton cyclotron associated with a new target design for neutrontherapy ; 10th. Int. Conf. on Cyclotron and their applications, East Lansing, 1984, P. 475.